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**Behavioral and electrophysiological indicators of auditory distractibility in children with ADHD and comorbid ODD**

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## ABSTRACT

Involuntary switching of attention to distracting sounds was studied by measuring effects of these events on auditory discrimination performance and event-related brain potentials (ERPs) in 6–11-year-old boys with Attention Deficit - Hyperactivity Disorder (ADHD) and comorbid Oppositional Defiant Disorder (ODD) and in age matched controls with no respective diagnoses. The children were instructed to differentiate between two animal calls by pressing one response button, for example, to a dog bark and another button to a cat mew. These task-relevant sounds were presented from one of two loudspeakers in front of the child, and there were occasional task-irrelevant changes in the sound location, that is, the loudspeaker. In addition, novel sounds (e.g., a sound of hammer, rain, or car horn) completely unrelated to the task were presented from a loudspeaker behind the child. Task-irrelevant novel sounds were found to decrease response accuracy and prolong reaction times to subsequent target sounds. These distraction effects were larger in the ADHD group than in the control group. In both groups, a biphasic positive P3a response was observed in ERPs to the novel sounds. The later part of the P3a had a larger amplitude and longer duration over the frontal scalp areas in the ADHD group than in the controls, suggesting stronger attention switch towards the novel sounds in the ADHD group. The present study indicates that children with ADHD and comorbid ODD suffer from a same kind of distractibility as found in previous studies for children with ADHD without systematic comorbid ODD.

*Keywords:* ADHD; ODD; attention; orienting; distractibility; ERP; P3a

## 1. Introduction

Attention Deficit - Hyperactivity Disorder (ADHD) is a neuropsychiatric disorder characterized by inattention, impulsivity, and hyperactivity (DSM-V American Psychiatric Association). These core problems emerge already in childhood and persist into adulthood and they often lead to difficulties in academic, occupational, and social life. The prevalence of ADHD is 4–10 per cent and it is 1–3 times more common in males than in females (Skounti et al., 2007). Various comorbid disorders in ADHD are common (Gillberg et al., 2004). One of the most frequent comorbidities in ADHD is Oppositional Defiant Disorder (ODD). ODD is a psychiatric behavioural disorder where a child often actively defies adults' rules or requests, often loses temper and argues with adults (DSM-V American Psychiatric Association).

A person with ADHD has difficulties in tasks demanding sustained attention (Kemner et al., 1996). Increased distractibility has been proposed to be an underlying mechanism and one of the clinical characteristics of ADHD. For instance, children with ADHD typically have difficulties in concentrating on school lessons because environmental stimuli easily draw their attention away from the task at hand. Adams and colleagues (2009) used a virtual classroom environment to study the performance of children with and without ADHD and found a strong trend of children with ADHD identifying less targets correctly and making more commission errors. Similarly, there is evidence on abnormally distractible non-ADHD children showing abnormal orienting to non-attended stimuli (Kilpeläinen et. al., 1999).

There have been different suggestions on the cognitive and neural deficits that underlie this apparent distractibility. For example, it has been proposed that children with ADHD fail to inhibit stimuli extraneous to the task (Barkley, 1997). The failure to sustain attention in ADHD has also been explained with motivational factors (Carlson et. al., 2002) and with functional attempt to modulate underarousal (Zentall & Zentall, 1983). Gumenyuk and colleagues (2005) found that task-irrelevant

novel environmental sounds distract performance in a visual discrimination task more in children with ADHD than in control children, as indicated by a higher number of response omissions to visual target stimuli following a novel sound in children with ADHD. In a continuous performance study by Cassuto and colleagues (2013), children with and without ADHD differed in their reactions to distracting stimuli. All kinds of distracting stimuli increased the rate of omission errors in children with ADHD, while the children without ADHD were distracted only by combined visual and auditory distractors. However, Van Mourik and colleagues (2007), in turn, reported less response omissions in children with ADHD than in controls after task-irrelevant novel sounds. This contradicting finding might be explained by their experimental design: They presented the task-irrelevant novel sounds via a loudspeaker next to the screen where the visual target stimuli appeared (van Mourik, personal communication, 2007) while Gumenyuk and colleagues (2005) presented their task-irrelevant novel sounds via headphones, that is, from a different direction than their task-relevant visual stimuli that occurred on a screen in front of the child. Thus, environmental sounds may distract task performance more in children with ADHD than in healthy controls when they draw attention away from the direction of target stimuli, but may improve performance of children with ADHD when these sounds draw attention towards the location of targets (for a similar findings in healthy adults, see Alho et al., 2015; Salmi et al., 2009). In sum, both these effects may be explained by enhanced involuntary attention to the direction of task-irrelevant environmental sounds in children with ADHD.

In the present study, children with ADHD and comorbid ODD were compared with control children in an auditory distraction task where distractibility was evaluated by measuring task performance and the event-related brain potentials (ERPs). Sounds deviating acoustically widely from preceding repetitive sounds elicit a P3 deflection of the ERP called the P3a or novelty P3 (Squires, Squires & Hillyard, 1975; Sams et al., 1985; Friedman, Cycowicz, & Gaeta, 2001). The P3a has been suggested to be associated with detection and evaluation of novelty (Escera et al., 2000) and with involuntary attention switching, since P3a-eliciting task-irrelevant novel sounds distract task performance in children (Gumenyuk et al., 2004, 2005) and adults (Escera et al., 2000). The P3a often

follows an enhanced N1 response (peak around 100 ms from sound onset), presumably caused by a large number of auditory-cortex neurons activated by novel sounds but not by the repetitive sound (e.g., Alho et al., 1998) and/or the mismatch negativity (MMN), which has been associated with preattentive detection of changes in the auditory input (e.g., Näätänen et al., 2007).

The P3a to novel sounds has two phases (Alho et al, 1998; Escera et al, 1998; Yago et al, 2003). The early P3a (eP3a) reaches its maximum around 200–300 ms from sound onset over central scalp areas and has its main sources presumably in the auditory cortex and parietal lobe as indicated, e.g., by source analysis of magnetoencephalographic (MEG) recordings and by current density analysis of ERP scalp distribution (Alho et al, 1998; Yago et al., 2003). The subsequent late P3a (lP3a) has a wider scalp distribution and an additional contribution from the frontal lobes (Yago et al., 2003). In other words, multiple brain areas are involved in involuntary attention switching and novelty detection. This appears to be true also in children.

In their aforementioned study, Gumenyuk and colleagues (2005) observed over left fronto-central scalp areas significantly smaller amplitudes of the eP3a to novel sounds in the children with ADHD than in the controls, presumably due to an overlapping negative ERP component elicited in the ADHD group, and in parietal scalp areas a significantly larger lP3a to novel sounds in the children with ADHD (see also van Mourik et al., 2007). Previous studies have also reported abnormal P3a amplitudes to novel sounds in other patient groups: Patients with closed head injuries (Kaipio et al., 1999), orbitofrontal brain lesions (Rule et al., 2002) and alcoholism (Polo et al., 2003) have enhanced P3a amplitudes to task-irrelevant novel sounds, while patients with dorsolateral prefrontal lesions show attenuated P3a responses (Knight et al., 1984).

In the present study, we used a new combination of the two distraction paradigms developed for ERP studies in children by Wetzel and colleagues (2004) and Gumenyuk and colleagues (2005). This was also the first time when auditory task performance was compared between ADHD and control children in a distraction paradigm. Wetzel and colleagues used a distraction paradigm successfully in 5-

year-old children. In their paradigm, the children were to differentiate two animal calls from each other. These task-related sounds were presented from one of two loudspeakers in front of the child, and there were occasional task-irrelevant changes in sound location, that is, an animal call was presented through the other loudspeaker. These changes in sound location caused deterioration of task performance. Gumenyuk and colleagues, in turn, presented 8–10-year-olds with a task-irrelevant tone or novel sound before each picture the children were to discriminate by a button press as an animal or a non-animal. The overall performance was less accurate in children with ADHD than in the controls and the children with ADHD had a higher number of omitted responses following a novel sound. In the present study, we combined these two previously used paradigms. Like in the study of Wetzel and colleagues, the children were to differentiate between two animal calls presented from one of two loudspeakers in front of the child, and there were occasional task-irrelevant changes in sound location. In addition to these sounds, we aimed to distract their performance by presenting from a loudspeaker behind the child task-irrelevant novel sounds similar to those used by Gumenyuk and colleagues (Fig. 1). We hypothesized that the novel sounds and task-irrelevant location changes in target sounds would distract children with ADHD and comorbid ODD more than control children and, further, whether the children with ADHD show abnormalities in ERPs to these distracting auditory events. Based on previous studies, we hypothesized that the ADHD group would be more distracted by the novel sounds and would therefore show longer reaction times, decreased hit rates, and/or increased rates of response errors to subsequent targets compared with the control group. Moreover, on the basis of results of Gumenyuk and colleagues (2005), we expected that ERPs to the novel sounds would show larger P3a responses in children with ADHD than in the controls indicating enhanced attention to distracting sounds, and perhaps a preceding enhanced frontally dominant negativity in the ADHD group.

[Figure 1 about here]

## 2. Results

### 2.1. Performance

Reaction times to animal calls became longer in both groups (13 boys in each group) as the experiment proceeded from its first phase to the second phase and further to the third phase (blocks 1–6 vs. blocks 7–12 vs. blocks 13–18;  $F(2,48) = 15.30$ ,  $p < 0.001$ ; Fig. 2a). This was indicated by hit reaction times to animal calls delivered from a standard location and not preceded by a novel sound onset within 1500 ms before call onset (in the following, these animal calls will be called *standard sounds*). Moreover, the reaction times were significantly longer in the ADHD group than in the control group ( $F(1,24) = 21.79$ ,  $p < 0.001$ ) there being no significant Group X Phase interaction. In addition, the precedence of the experiment diminished significantly the percentage of hit responses ( $F(2,48) = 8.51$ ,  $p < 0.01$ ; Fig. 2b). Furthermore, there were significantly less hit responses in the ADHD group than in the controls ( $F(2,48) = 10.39$ ,  $p < 0.004$ ). There was also a significant Group x Phase interaction ( $F(2,48) = 6.74$ ,  $p < 0.003$ ), hit rate diminishing more in the ADHD group than in the control group as the experiment proceeded. In addition, the percentage of wrong responses increased during the experiment ( $F(2,48) = 6.03$ ,  $p < 0.008$ ; Fig. 2c) but there was no significant Group x Phase interaction, this percentage being larger in the ADHD group throughout the experiment ( $F(1,24) = 9.83$ ,  $p < .004$ ). Finally, the percentage of misses (Fig. 2d) increased in both groups during the experiment ( $F(2,48) = 4.68$ ,  $p < 0.02$ ), but there was also a significant Group x Phase interaction ( $F(2,48) = 6.22$ ,  $p < 0.006$ ), the percentage of missing responses increasing more in the ADHD group than in the controls towards the end of experiment.

[Figure 2 about here]



There was a significant, expected, difference between the groups in the decrease of the percentage of hit responses to *distracted standards* (animal calls from the standard loudspeaker preceded by a novel sound onset within 1500 ms before call onset) in relation to non-distracted standards (Fig. 3): The ADHD group's hit percentage was decreased more after distraction than that of the controls ( $t(24)=2.01$ ,  $p < 0.03$ ).

However, it is not clear whether the stronger decrease in performance accuracy in the ADHD group was caused by a tendency to give more wrong responses or to omit responses after a novel sound as there were no significant group differences in the effects of preceding novel sounds on percentages of wrong or missing responses to standard sounds.

As also expected, the reaction times to standard sounds tended to be prolonged more by preceding distracting novel sounds in the ADHD group than in the control group although this effect did not quite reach statistical significance ( $t(24)=1.56$ ,  $p < 0.06$ ).

There were no significant group differences in effects of infrequent location deviances in animal calls (see Fig. 1) on reaction times or percentages of hits, wrong responses or missing responses.

[Figure 3 about here]

## **2.2. Event-related brain potentials**

Fig. 4 shows grand-average ERPs in the ADHD and control groups to standard, deviant and novel sounds at different electrodes. The ERPs to standard sounds were quite similar in the two groups. In the grand-average ERPs to deviant sounds, there was a small MMN-like response for both groups, i.e., the ERPs to deviant sounds showed more negative amplitudes than the ERPs to standard sounds this effect being largest at 250–300 ms from sound onset. However, this difference was not further analyzed because of a too low signal to noise ratio in this ERP difference in individual children.

[Figure 4 about here]

As seen in Fig. 4, the ERPs to distracting novel sounds differed widely from the ERPs to standard sounds. To study these effects, ERP difference waves were calculated for each child by subtracting the ERPs to standard sounds from ERPs to novel sounds. The grand-average ERP difference waves are shown for each group in Fig. 5. As seen in Fig. 5, there was an MMN-like response to the novel sounds at 200–250 ms from sound onset. However, this response was not further analysed because it was presumably contaminated by differences in the obligatory ERP responses to the standard and novel sounds differing markedly in their spectral structure and spatial location (cf. Alho et al., 1998; Näätänen & Picton, 1987).

As in previous studies (e.g., Gumenyuk et al., 2005), the ERP difference waves for novel sounds showed a P3a response consisting of two parts. The early P3a (eP3a) peaked between 350–400 ms and was maximal over the frontal and central scalp areas (Fig. 5). Group differences in mean eP3a amplitudes measured as mean difference wave amplitudes over 300–350 and 350–400 ms from sound onset did not reach significance. However, at the eP3a latencies, the difference waves of the ADHD group were negatively displaced in relation to the difference waves of the control group over the frontal scalp, especially at the left frontal electrode F3 (cf. Gumenyuk et al., 2005). Although this effect did not reach statistical significance, it caused a non-significant Group x Frontality x Laterality interaction found in an ANOVA for the novel-standard difference wave amplitudes at 300–350 ms from sound onset ( $F(4,96) = 2,042, p < 0.11$ ).

The eP3a was followed by the late P3a (IP3a) with its peak after 400 ms from sound onset. The IP3a appeared to have larger amplitudes and last longer in the ADHD group than in the controls at the frontal electrode sites. This was confirmed by ANOVAs for difference wave amplitudes. These ANOVAs indicated a significant Group x Frontality interaction at 500–550 ms ( $F(2,48) = 3.83, p < 0.05$ ) and 550–

600 ms ( $F(1,24) = 5.10, p < 0.02$ ) from sound onset, and an almost significant Group x Frontality interaction already at 450–500 ms ( $F(1,24) = 3.18, p < 0.08$ ).

[Figure 5 about here]

### 3. Discussion

The present study showed that performance in an auditory discrimination task is distracted more by task-irrelevant novel sounds in children with ADHD and ODD than in control children. Overall the ADHD group had slower reaction times, more wrong responses and more omitted responses than the control group resulting in lower rates of hit responses in the ADHD group. Also, the performance of the ADHD group became slower and more inaccurate as the experiment proceeded, whereas the performance of the control group remained relatively accurate throughout the experiment. Moreover, performance accuracy was decreased significantly more by distracting novel sounds in the ADHD group than in the control group.

Abnormal distractibility in the ADHD group was also evident in ERPs to novel sounds. As in previous studies (e.g., Gumenyuk et al., 2005), the P3a to the novel sound consisted of two parts, the eP3a and the IP3a. The IP3a showed larger amplitudes and continued longer over the frontal and especially over the left frontal scalp areas in the ADHD group than in the control group, indicating a stronger (or more frequent) attention switching towards the distracting novel sounds or problems of reorienting attention back to the task after a distracting novel sound. This difference might be related to enhanced automatic encoding and classification of novel sounds proposed by Escera and colleagues (2000). In previous studies, such frontal left-hemisphere dominant abnormalities in response to auditory stimulus changes and novel sounds have been found in children with ADHD (Oades, 1998; Gumenyuk et al., 2005). The present study shows such differences also in children with ADHD and comorbid ODD.

The eP3a to the novel sounds, in turn, tended to have smaller amplitudes in the ADHD group than in the control group although this effect did not reach significance. Perhaps similarly to the results of Gumenyuk and colleagues (2005), the present non-significant difference was caused by an enhanced left-hemisphere dominant negative ERP component overlapping with the eP3a to the novel sounds in the ADHD group. As suggested by them, such negativity might be associated with a deficit in suppressing automatic identification of distracting sounds (cf. Escera et al., 2000). However, the present group difference in ERPs to novel sounds at the eP3a latencies must be interpreted cautiously as this difference may get contribution from differences in obligatory (exogenous) ERP components between standard sounds and novel sounds that differed substantially in their location and spectro-temporal structure from the standard sounds (cf. Alho et al., 1998; Näätänen & Picton, 1987).

Although the present findings largely replicate the findings of Gumenyuk and colleagues (2005), it should be noted that the eP3a and the IP3a had shorter latencies in their study than in the present one. In Gumenyuk and colleague's study, these ERP components peaked between 180-250 and 300-350 ms from novel sound onset, respectively. The latency differences between their study and the present one might be explained by different tasks performed by the children. In Gumenyuk and colleague's study, children performed a visual animal/non-animal discrimination task, whereas in the present study, the discrimination task was auditory. Attentive processing of the task-relevant animal calls in the present study may have delayed processing of the task-irrelevant novel sounds more than the attentive processing of visual stimuli in their study. In addition, in the study of Gumenyuk and colleagues, the children with ADHD did not have any systematic comorbid disorders, whereas in the present study all children with ADHD had also ODD, and some even other comorbid disorders. Therefore differences in the comorbid diagnoses of the participating ADHD groups might partly explain the ERP latency differences between the present study and their study.

## **4. Conclusions**

The present study shows that children with ADHD and comorbid ODD suffer from distractibility. This distractibility was observed both in the behavioral and electrophysiological measures. In the present study, the distracting novel sounds occurred from a totally different direction than the task-relevant sounds and were irrelevant to the task like many distracting environmental sounds in everyday situations, for example, in a classroom or at work places. It seems that children with ADHD are more prone than controls to switch their attention to unexpected environmental events and keep it longer in that direction which then interferes with their performance. In addition to these findings, the present comparison of performance accuracy during the first, second and third phase of the experiment suggests that inaccuracy of task performance of children with ADHD increases with increasing task duration and consequent increasing fatigue. It is also possible that the children with ADHD had more motivational and/or optimal arousal level problems which affected their performance. More research is needed to reveal the neural and cognitive functions of distractibility.

## **5. Experimental procedures**

### ***5.1. Participants***

Fourteen 6–11-year-old children with ADHD and 16 age-matched control children participated in the study. One ADHD and one control child were excluded from the analyses due to a lack of co-operation with the experimenters and two additional control children were excluded because of technical difficulties in EEG data collection. The remaining ADHD group consisted of 13 right-handed boys between 6–11 years of age (mean 9 years 7 months). The remaining control group consisted of 13 right-handed boys who were 7–11 years old (mean 9 years 5 months). All participants were in the age-

appropriate grade at school. Ten out of 13 children in the ADHD group, but none in the control group, participated in a special education program.

The children with ADHD were recruited from the Department of Child Neurology of the Helsinki University Central Hospital (HUCH). A licensed child neurologist gathered the ADHD group during a time period from fall 2004 to spring 2005 out of the children coming to the clinic with ADHD symptoms using the exclusion criteria of the international atomoxetine study (Bangs et al., 2008): All children with ADHD had been diagnosed according to DSM-IV (American Psychiatric Association, 1994) criteria for ADHD and Oppositional Defiant Disorder (ODD), and in addition could have comorbid neurological disabilities, for instance, learning difficulties, but no other psychiatric disorders according to the exclusion criteria (Bangs et al., 2008). Those children with ADHD who were on stimulant medication (9 out of 13 children) were withdrawn from it at least three days before the experiment. The control group was recruited from ordinary primary schools by sending letters, which described the study and invited volunteers to participate in it. Control children had no diagnosed psychiatric or neurological disorders and they had normal hearing and normal or corrected-to-normal vision. This was controlled by questionnaires filled by their parents. The control children were compensated with 6 € per hour for their participation. The present study is part of an international atomoxetine study (Bangs et al., 2008) supported by Eli Lilly and Company (Indiana, USA) and was accepted by the HUCH Institute at the Helsinki University Central Hospital. Written informed consents were obtained from all the children's parents and the children gave their consents orally. The National Advisory Board on Health Care Ethics approved the protocol for the children with ADHD and the Ethical Committee of the Department of Psychology, University of Helsinki, approved the protocol for the control children.

The children's general intellectual ability was assessed with the Wechsler Intelligence Scale for Children 3<sup>rd</sup> edition (WISC-III, Wechsler, 1999). Full-scale intelligence quotient (FIQ) ranged from 94 to 136 (mean 114, standard deviation 12) in the control group and from 76 to 113 (mean 94, standard deviation 10) in the ADHD group, there being a significant between-group difference ( $t(24) = 4.47$ ,  $p < 0.001$ ). It is very common that children and adults with ADHD have lower intelligence quotients than

controls. This has been explained by lowered processing speed and general problems in executive functions in ADHD which deteriorates performance in intelligence tests (Laasonen et al., 2009).

## **5.2. Stimuli and procedure**

The experimental setup (Fig. 1) was a modified version of Wetzel and colleagues' (2004) paradigm, which is a child-appropriate version of Schröger and Wolff's (1998) distraction paradigm. Different animal calls (a cat, dog, and crow; duration of each call 400 ms, intensity at the children's ears ca. 70 dB SPL, rise and fall times 10 ms) were presented through loudspeakers, located to the left and right from a computer screen in front of the child (distance of the screen from the child 90 cm, distance of the loudspeakers from the center of the screen 70 cm). The calls were presented with a stimulus onset asynchrony (SOA) of 3200 ms from one loud-speaker at a time, the sounds being presented mostly from one direction (standard sounds), and occasionally ( $p=0.11$ ) from the other direction (deviant sounds), the loudspeakers for standard and deviant sound locations being varied randomly from block to block. Task-irrelevant novel sounds were presented in an independent sequence with an SOA of 12–18 s from a third loudspeaker behind the child (distance from the child's head 90 cm). The novel sounds were drawn randomly from a pool of 140 different environmental sounds (Gumenyuk et al., 2005) such as sounds of hammer, rain, door, and car horn. The duration of each novel sound was 200 ms (with rise and fall times of 5 ms) and the maximum intensity at the children's ears was ca. 70 dB SPL. Each novel sound was presented only once or twice during the entire experiment.

In each block, two randomly selected animal calls were presented in a random order with equal probabilities. The children were instructed to look at the computer screen and to press with their right hand on every trial one of two buttons in response to one animal and the other button to the other animal. Thus the total duration of the experiment was approximately 36 minutes excluding short breaks between the blocks. After each response the children were given feedback on their performance by showing a happy or sad smiley on the screen for 800 ms. A happy smiley appeared after a correct

button press within 2000 ms after animal call onset and a sad smiley after an incorrect or missing button press. Before each block, a short practice was run to ensure that the child was able to perform the task. One of the experimenters was present in the experimental chamber with the child throughout the experiment.

### **5.3. Analysis of task performance**

Accuracy and speed of children's performance was analyzed as follows. Standard-location sounds that occurred together or right after a novel-sound, i.e., standard-location sounds with their onset at 0-1500 ms after a novel sound onset, were classified as *distracted standards* and were analyzed separately. Other standard sounds, which had no novel sound onset occurring within 1500 ms before them, were classified as *standards*. Deviant-location sounds with onset 0-1500 after novel sound onset were excluded from the analyses due to their small number. Other deviant-location sounds were classified as *deviants*. A correct button press within 200–2000 ms after an animal call onset was classified as a hit.

To study possible effects of fatigue or learning on performance during the experiment, percentages of hit, wrong and missing responses, as well as hit reaction times to standards were compared between the groups and between the first phase (blocks 1 and 2), second phase (blocks 3 and 4), and third phase (blocks 5 and 6) of the experiment with an analyses of variance (ANOVA). Greenhouse-Geisser corrections were used for the p-values when appropriate. However, the original degrees of freedom are reported with the F-values.

To study effects of novel sounds on performance, distracted-standard-minus-standard differences were calculated for each child's percentages of hit, wrong, and missing responses and hit reaction times to minimize effects of individual variation in response speed and accuracy. These distraction measures were compared with one-tailed t-tests, as according to our hypotheses, reaction



times should be prolonged, hit rates decreased, and percentages of wrong and missing responses increased more by distracting sounds in the ADHD group than in the controls.

#### **5.4. Recording and analysis of ERPs**

The electroencephalogram (EEG; 0.1–100 Hz, sampling rate 1000 Hz) was recorded from left, midline and right frontal (F3, Fz, and F4, respectively), central (C3, Cz, and C4, respectively) and parietal (P3, Pz, and P4, respectively) scalp sites and from the left and right mastoids (LM and RM, respectively). The reference electrode was placed on the tip of the nose. Continuous EEG was band-pass filtered at 1–40 Hz. ERPs were obtained separately for standard, deviant, and novel sounds by averaging EEG epochs over 700-ms periods starting 100 ms before each sound onset. To remove epochs with remaining extracerebral artifacts (caused, e.g., by eye movements, blinks, or muscle activity), epochs with voltages exceeding  $\pm 150$  mV (at any channel) were excluded from the analysis. Also, epochs for any standard or deviant sound with its onset between 600 ms before and 2000 ms after a novel sound onset, were excluded from the analysis as these epochs might be affected by overlapping brain activity elicited by a novel sound. The averaged ERPs were low-pass filtered at 20 Hz, and re-referred to the average of the measurements of the left and the right mastoids.

ERP difference signals for each participant were obtained by subtracting ERPs to standard sounds from ERPs to novel sounds. Amplitudes of these difference signals were measured as mean amplitudes. Between-group differences in the amplitudes were examined with ANOVAs including electrode factors Frontality (frontal F3, Fz, F4 vs. central C3, Cz, C4 vs. parietal P3, Pz, P4 electrodes) and Laterality (left-hemisphere F3, C3, P3 vs. midline Fz, Cz, Pz vs. right-hemisphere F4, C4, P4 electrodes). Greenhouse-Geisser corrections were used for the p-values when appropriate. However, the original degrees of freedom are reported with the F-values.

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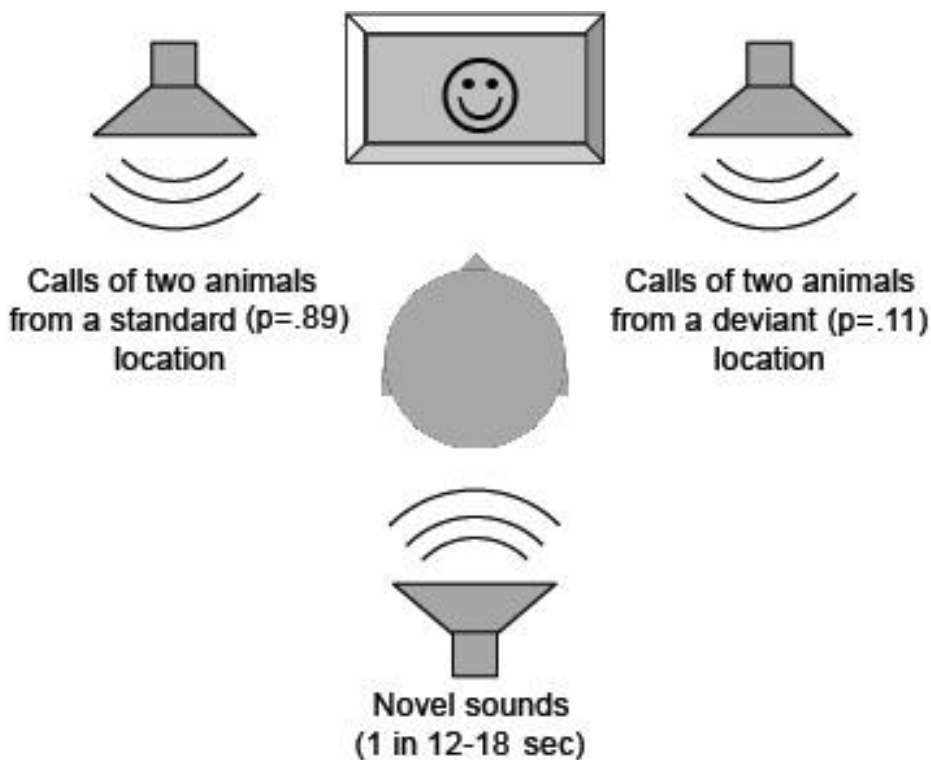


Figure 1. A schematic illustration of the auditory distraction paradigm used in the present study (for details, see text). Calls of two animals (a dog and cat, cat and crow or crow and dog in different blocks) that the children were instructed to discriminate by pressing either one of two response buttons were delivered at the rate of one call in 3.2 s mostly ( $p=.89$ ) from a standard loudspeaker and occasionally ( $p=.11$ ) from a deviant loudspeaker in front of the child (in half of the blocks, the right loudspeaker, and in the other half the left loudspeaker, was the standard location). Between these loudspeakers there was a screen where a “smiley” gave feedback to the children on their performance in this task. Additional task-irrelevant novel sounds (e.g., a sound of hammer, rain or car horn) were delivered at the rate of one sound in 8-12 s from a loudspeaker behind the child. Each block included 36 animal calls and ca. 7 novel sounds and lasted slightly less than 2 minutes. There were 6 blocks for each of the three animal combinations (cat and dog, cat and crow, dog and crow). After each response, the children were given feedback on their performance by showing a happy or sad smiley on the screen. A happy smiley appeared after a correct button press and a sad smiley after an incorrect or missing button press.



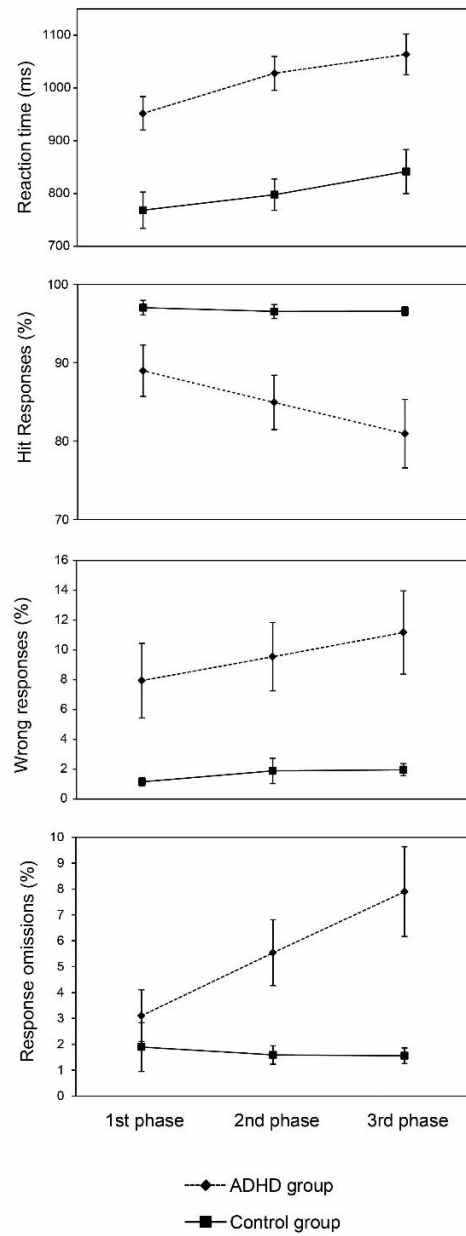


Figure 2. From top to bottom: Mean reaction times, and percentages of hits, wrong responses and missing responses in the ADHD and control groups for the standard sounds in the first, second and third phase of the experiment. Error bars indicate standard errors of the mean.

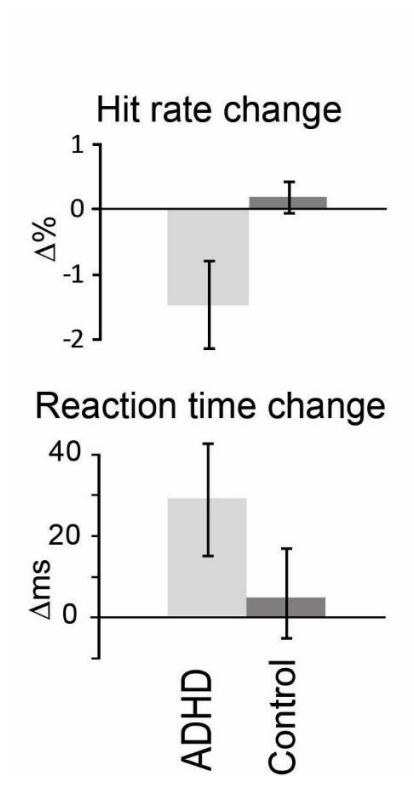


Figure 3. Top: Mean change in the percentage of hits in the ADHD and control groups for distracted standard sounds. Bottom: Mean change in the reaction times in ADHD and control groups for distracted standard sounds.

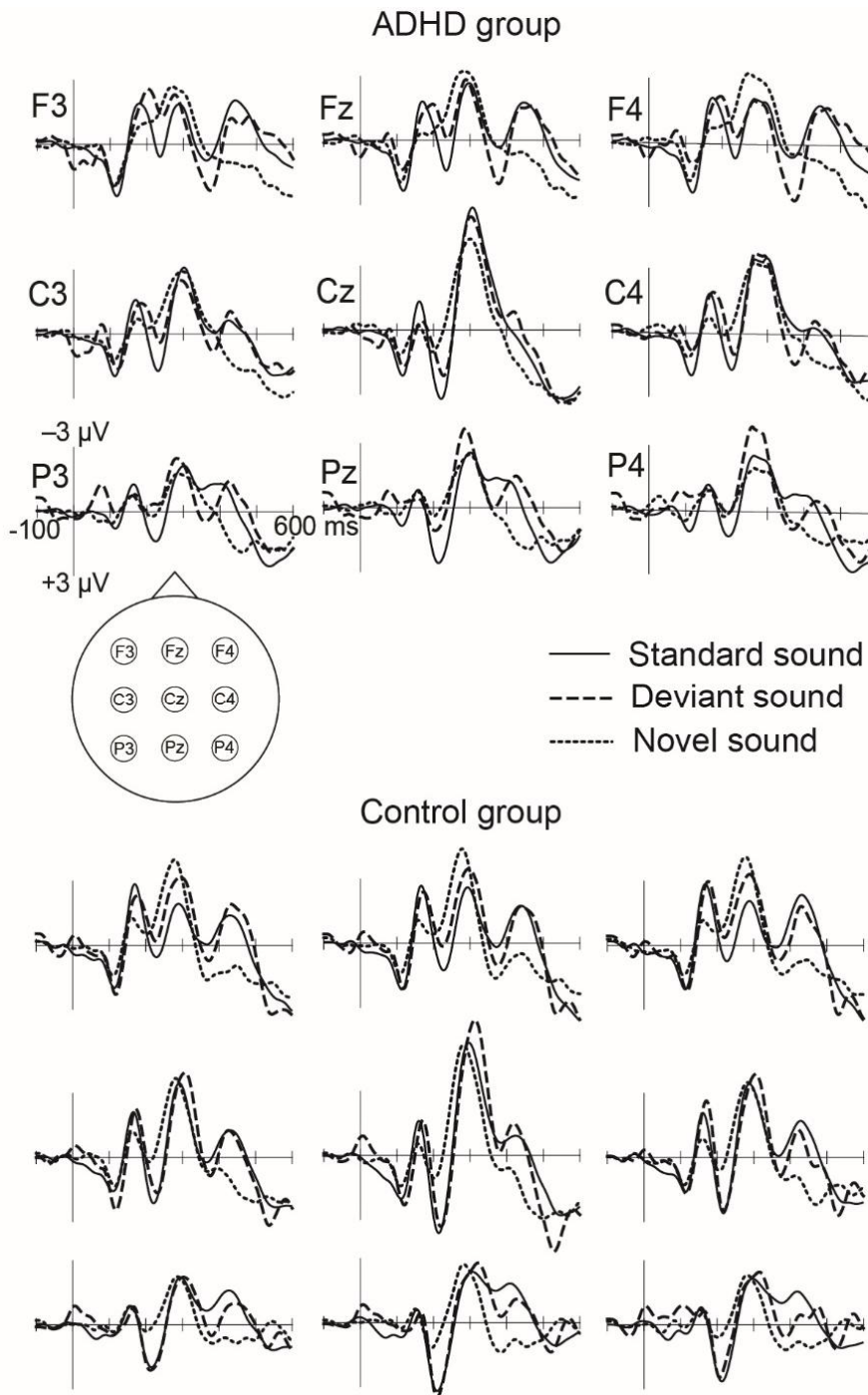


Figure 4. Grand-average ERPs to the standard (continuous lines), deviant (dashed lines) and novel sounds (dotted lines) at the 9 scalp electrodes in the ADHD group (top) and control group (bottom).

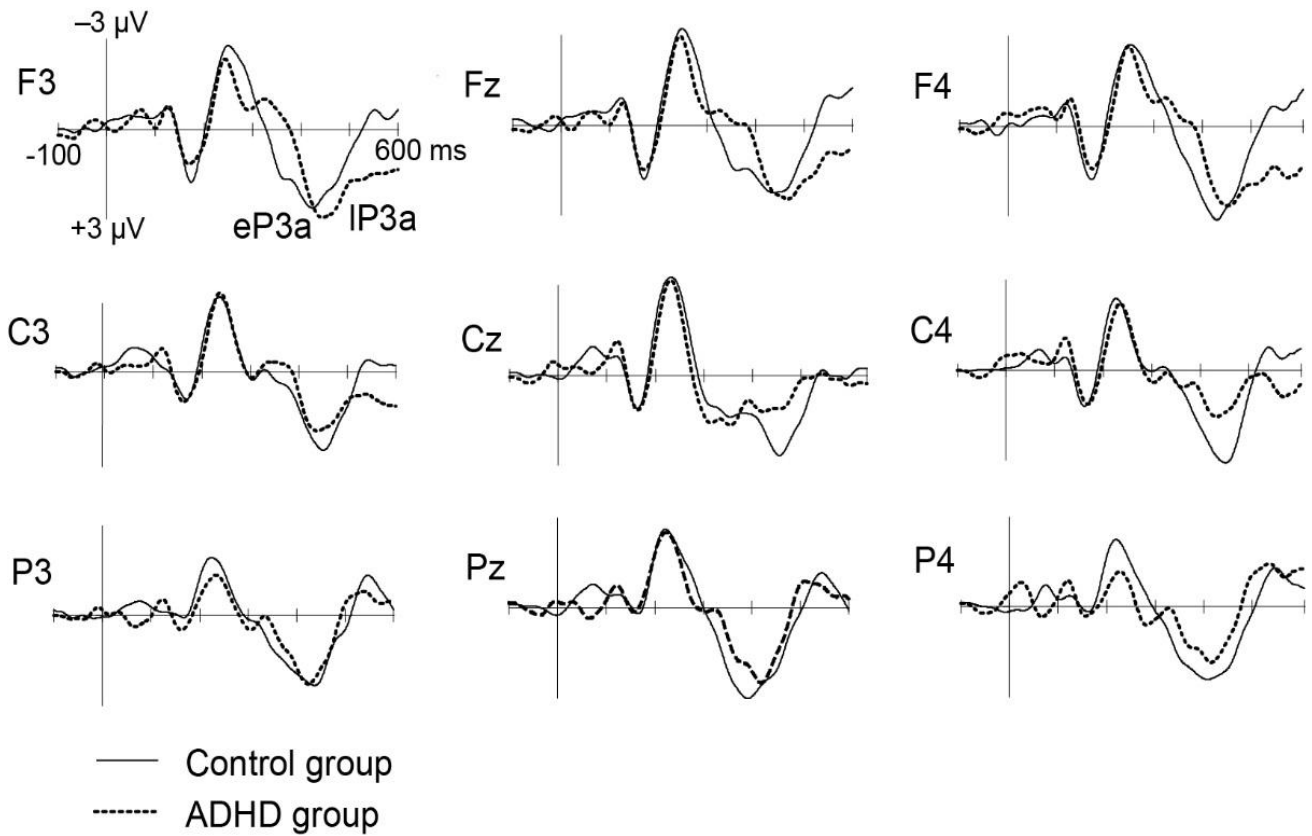


Figure 5. Grand-average ERP difference waves obtained by subtracting the ERPs to standard sounds from the ERPs to novel sounds in the ADHD group (dotted lines) and control group (continuous lines).